Correlations Between Neutral and Ionized Solar Wind

B.M. Pilkerton

Universities Space Research Association, Seabrook, MD 20706; and NASA Goddard Space Flight Center, Greenbelt, MD 20771

M.R. Collier and T.E. Moore

NASA Goddard Space Flight Center, Greenbelt, MD 20771

Abstract

We report results of a statistical study correlating ionized solar wind (ISW) fluxes observed by ACE during late 2000 and throughout 2001 with neutral solar wind (NSW) fluxes observed by IMAGE/LENA over the same period. The average correlation coefficient between the neutral and ionized solar wind is 0.66 with correlations greater than 0.80 occurring about 29% of the time. Correlations appear to be driven by high solar wind flux variability, similar to results obtained by in-situ multi-spacecraft correlation studies. In this study, however, IMAGE remains inside the magnetosphere on over 95% of its orbits. As a function of day of year, or equivalently ecliptic longitude, the slope of the relationship between the neutral solar wind flux and the ionized solar wind flux shows an enhancement near the upstream direction, but the symmetry point appears shifted toward higher ecliptic longitudes than the interstellar neutral (ISN) flow direction by about 20 degrees. The estimated peak interstellar neutral upstream density inside of 1 AU is about $7 \times 10^{-3}\mathrm{cm}^{-3}$.

Key words: solar wind/magnetosphere interactions, neutral atom imaging, space weather

1 Introduction

The Low Energy Neutral Atom (LENA) imager, designed to study primarily plasma heating in the terrestrial ionosphere (Moore et al., 2000), has proven useful for the study of a diverse population of physical systems including the solar wind and magnetosheath, Earth's ring current, and interstellar neutral atoms (Moore et al., 2003). Here, we report results of a statistical study correlating neutral solar wind with ionized solar wind.

Neutral solar wind (NSW) forms when solar wind ions charge exchange with neutral atoms in the inner solar system ($H^+ + H \longrightarrow H + H^+$). The result is a newly created neutral atom that remains largely on its initial trajectory and uninfluenced by electric or magnetic fields. There are at least three solar wind charge exchange media that contribute to the generation of the neutral solar wind: a relatively symmetric dust source close to the Sun, interstellar neutral atoms, and planetary exospheres, in this case the Earth's, but NSW has also been observed at Mars (Barabash et al., 2004).

Designed to observe converted oxygen and hydrogen atoms with energies in the 10 eV to 1 keV range, LENA has been shown to respond to hydrogen energies as high as $\sim$3 keV, due to sputtering interactions with the tungsten conversion surface used to convert the neutral atoms to negative ions (Moore et al., 2003). LENA's neutral solar wind response was first noted during an event on June 8, 2000 in which an increased instrument response from the direction of the Sun during a coronal mass ejection at Earth was found to be uncorrelated with ultraviolet emission from the Sun or suprathermal ions, leading to the interpretation that LENA was imaging neutral atoms from the solar wind (Moore et al., 2001; Collier et al., 2001). Energetic neutral atom (ENA) simulations also supported the interpretation that observable fluxes of solar wind neutral atoms are created by solar wind ions charge exchanging with hydrogen atoms in the magnetosheath and upstream of the Earth's bowshock and calculations have shown that solar wind charge exchange with interstellar neutral atoms and dust creates observable NSW fluxes as well.

2 Method

The data in this study cover days 298 - 331 of year 2000, and days 55 - 145 and days 231 - 320 of year 2001, comprising a total data set of 360 IMAGE orbits. These periods were chosen because they were shortly after launch and because LENA was in only two similar instrument states during this time so the instrument efficiencies are well-characterized. During the summer and winter months, when the direct Sun signal is out of LENA's $\pm 45°$ FOV, LENA NSW data were not available. Although the instrument would occasionally be interrupted near apogee by over-saturation due to high energy particle contamination, the data set used is essentially continuous.

The LENA data were taken an hour around apogee, about 8 R_E nearly above the polar region. Apogee was picked to avoid the effects of magnetospheric neutral atom populations, to decrease the likelihood of charged particle contamination, and to minimize spacecraft motion over the periods of interest. We choose a look "window" of $\pm 40°$ (10 sectors in spin angle) in the Sun direction to ensure full spatial coverage of the Sun signal.

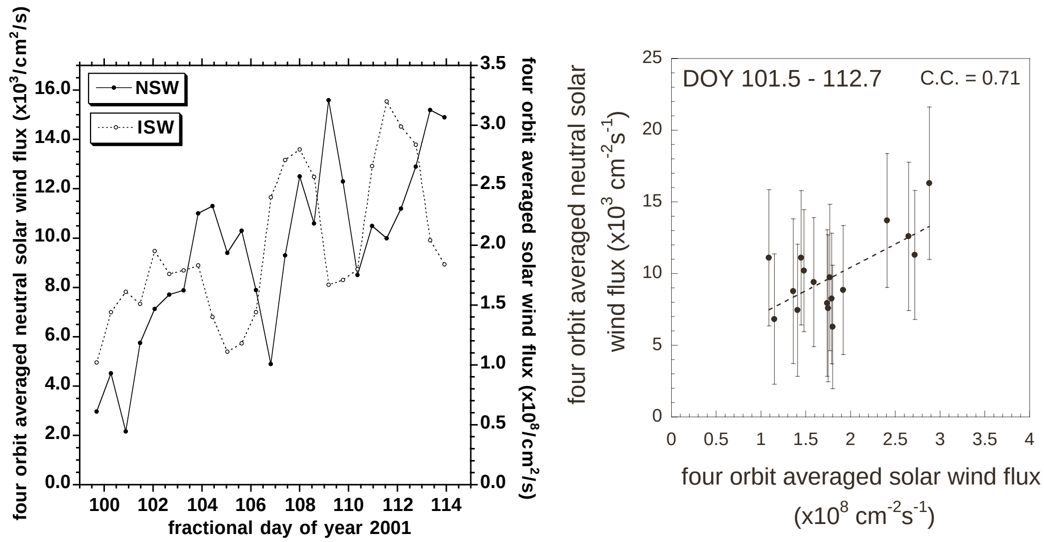

Fig. 1. (left panel) Plot of neutral and ionized solar wind fluxes versus time for a typical data set. (right panel) The scatter plot between the ACE and LENA data at the time of peak correlation.

Solar wind plasma data were taken from the SWEPAM instrument aboard the Advanced Composition Explorer (ACE), located upstream $1.5\text{x}10^6$ km at the first Lagrange point (L1). The ACE solar wind data were taken an hour before LENA's apogee time to allow for the plasma to traverse from the spacecraft to the Earth. LENA and ACE data were four-orbit running averaged to smooth short term and statistical fluctuations in the data. Furthermore, because solar wind ions can charge exchange anywhere between the Sun and the Earth, at which point the neutral atoms travel independently of the plasma with different energies arriving at 1 AU at different times, long period averages may be necessary to correlate the non-exospheric-generated NSW with the ISW. An interval of about ten days was chosen for each scatter plot, because this provides about 17 data points, sufficient to establish a meaningful correlation. The method yielded 174 data ranges or scatter plots which comprise the data of this study.

The LENA NSW data show an annual enhancement from about DOY 120 to day 250 (Collier et al., 2003) which has been interpreted as due to solar wind charge exchange with interstellar neutrals (the Sun is outside LENA's field of view from about DOY 145 - 231 2001). This type of an annual enhancement in the upstream region at 1 AU is expected because hydrogen overcomes the effects of charge exchange and photoionization most readily when it flows directly toward the Sun (e.g. Bzowski et al., 1996). During the period of enhancement when the Sun is in LENA's field of view, we apply the same method of analysis, but subtract off the secular trend in the data using a gaussian fit to the upstream enhancement. This "gaussian-detrended" data is then corre-

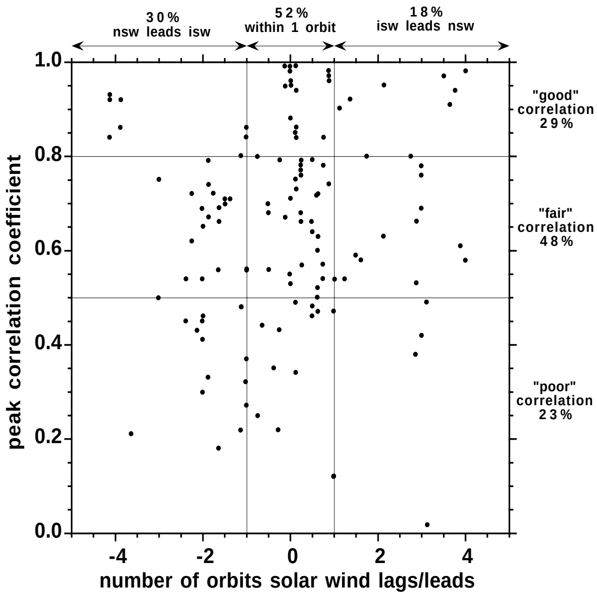

Fig. 2. Peak correlation coefficients for all data in this study.

	Correlation
flux	0.66
density	0.59
RAM pressure	0.54
velocity	0.43

Table 1. Neutral solar wind flux correlated with solar wind parameters for the entire data set.

lated with the ionized solar wind like the other neutral solar wind data, so that the analysis only considers fluctuations on top of these secular trends.

Because NSW formation can occur anywhere between the Sun and Earth, correlation coefficients were computed over each interval as a function of orbits lagged where an IMAGE orbit is about 14 hours. This consisted of incrementing the solar wind data ± 5 orbits and computing a correlation coefficient for each increment. The correlation data were then interpolated to create a continuous curve. The maximum correlation from this curve was then deduced along with the corresponding lag designation. Negative lag means the neutral solar wind leads the plasma, while positive lag means the plasma is leading the neutrals. The left panel of Figure 1 shows a sample plot of neutral and ionized solar wind fluxes versus time. The right panel of Figure 1 shows the corresponding scatter plot depicting a "fair" ($0.5 <$ peak C.C. < 0.8) correlation.

3 Results

3.1 Overview of the neutral solar wind correlations

Results from the study show that good correlations are found 29% of the time, fair correlations are found 48% of the time and poor correlations are found 23% of the time with an average correlation coefficient of 0.66. Also, results

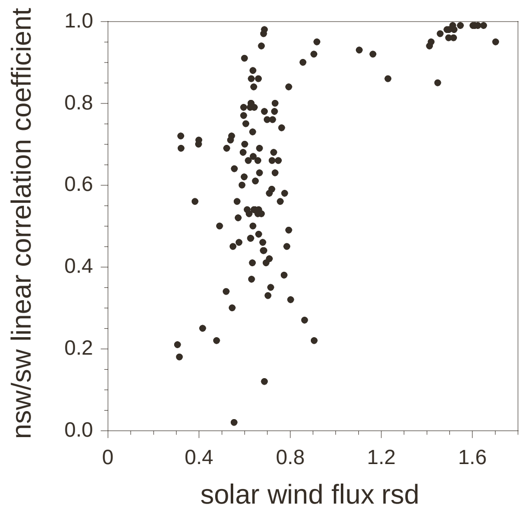

Fig. 3. Influence of the solar wind flux RSD on the NSW/ISW correlation coefficients

show that on average, the solar wind lag time is -0.2 $\pm$ 1.9 orbits, consistent with zero orbits. Figure 2 summarizes these results.

We also computed average correlation coefficients for various other solar wind plasma parameters. Table 1 lists the parameter of interest along with the average correlation coefficient over the data set. The neutral solar wind fluxes correlate best with the ionized solar wind flux. The solar wind ram pressure (ρv^2) correlates the worst among the density dependent parameters.

Additionally, for each ten day interval, the relative standard deviation (RSD), defined as the ratio between the standard deviation and the average value of the solar wind plasma parameters listed in Table 1 were computed. We found that higher values of the ionized solar wind relative standard deviation resulted in higher correlations. Figure 3 shows an example of this for solar wind flux. This result is similar to that found in other plasma correlation studies (Dalin et al., 2002; Richardson and Paularena, 2001, Zastenker et al., 2000; Paularena et al., 1998) that solar wind flux variability and density variability are the main drivers in multi-spacecraft plasma correlation studies.

3.2 Long-Term Trending of the NSW/ISW Slope

Figure 4 shows the slope of the NSW versus ionized solar wind scatter plot as a function of day of year for the year 2001 data. The slope peaks when the Earth is approximately upstream of the Sun in the ISN flow. However, the center of the peak appears to be at day 174, about twenty days later than expected based on the nominal upstream direction. If this shift is due to the ISN, then the shift may result from a heliospheric asymmetry effected by the interstellar magnetic field (Ratkiewicz et al., 1998). Such an asymmetry might produce a distinct secondary flow coming from a slightly different direction and with different properties than the main ISN flow (Collier et al., 2004).

Under the assumption that the upstream enhancement is due to solar wind charge exchange with interstellar neutral atoms, we can estimate the density of the interstellar neutrals, n_{ISN}, using the relationship:

$$n_{ISN} = \frac{1}{\sigma\lambda}\left[\frac{\Phi_{NSW}}{\Phi_{SW}}\right]_{slope} cm^{-3} \tag{1}$$

where σ is the charge exchange cross section of $1.6 \times 10^{-15} cm^2$, λ is the interaction scale length of 1 AU, and the fraction Φ_{NSW}/Φ_{SW} is taken to be the slope of the linearly correlated neutral solar wind and solar wind fluxes. The estimated peak interstellar neutral upstream density is about $7 \times 10^{-3} cm^{-3}$.

In the upstream direction if gravity balances radiation pressure, the interstellar neutral density at 1 AU, $n(1\ AU)$, is

$$n(1\ AU) \sim n_\infty \exp\{-\frac{\beta}{v_0} \cdot (1\ AU)\} \tag{2}$$

where β is the interstellar neutral loss rate at 1 AU, 5.5x10^{-7} s^{-1}, v_0 is the neutral flow speed, 20 km/s, and n_0 is the asymptotic hydrogen density, 0.12 cm^{-3} (Schwadron et al., 2000; Geiss and Witte, 1996). This results in a predicted density at 1 AU of about 2x10^{-3} cm^{-3}, roughly consistent with but lower than the inferred peak from Figure 4. Note that because of solar wind charge exchange and photoionization, the neutral density inside of 1 AU, which is primarily responsible for the formation of the neutral solar wind near the upstream direction, is significantly lower by more than an order of magnitude than the asymptotic hydrogen density far from the Sun.

4 Conclusions

Neutral solar wind fluxes observed by IMAGE/LENA were correlated with solar wind plasma parameters observed by ACE during late 2000 and throughout 2001. Neutral solar wind fluxes correlate best with the solar wind flux itself with good correlations (peak C.C. $>$ 0.8) occurring 29% of the time. The average peak correlation coefficient is 0.66. The average lag time is -0.2 $\pm$ 1.9 orbits, consistent with no orbital lag. The slope of the linearly correlated

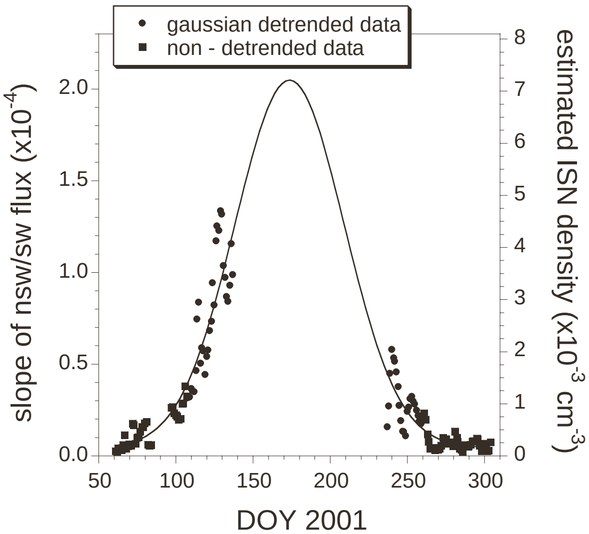

Fig. 4. The slope of the linearly correlated NSW/ISW flux plotted over time. The distribution is fit to a Gaussian with a mean day of year of 173.6±1.1, a peak of 2.0±0.2x10^{-4} and an e-folding width of 50±2 days.

neutral solar wind and solar wind flux when plotted as a function of day of year shows a peak shifted by about 20 degrees towards higher ecliptic longitudes than the interstellar neutral (ISN) flow direction with an estimated peak density of about $7 \times 10^{-3} cm^{-3}$.

Our results are similar to those of many in-situ multi-spacecraft correlation studies which show that solar wind plasma correlations are strongly driven by density and flux variability. However, unlike other solar wind monitors, IMAGE is almost never in the direct solar wind or magnetosheath. Estimates place the fraction of the orbits during 2000 and 2001 during which IMAGE did not leave the magnetosphere at >95% (J. Green, private communication). These results are supportive of an interpretation that attributes the bulk of the NSW seasonal variation to charge exchange between the ISW and the ISN flow, with the ISN flow having a density that peaks strongly at an ecliptic longitude near but shifted from the nominal upstream direction. This is consistent with the results of Collier et al. (2004) who discuss four data sets related to neutral atoms which also appear shifted toward higher ecliptic longitudes than the nominal upstream direction.

References

[1] Barabash, Stas, Holmström, Mats and the ASPERA Team, The latest results on the energetic neutral atoms and plasma of Mars from the ASPERA instrument

of Mars Express. 35^{th} COSPAR Scientific Assembly, p. 140, 2004.

[2] Bzowski, Maciej, Fahr, Hans J., Ruciński, Daniel, Interplanetary neutral particle fluxes influencing the Earth's atmosphere and the terrestrial environment. Icarus, 124, 209-219, 1996.

[3] Collier, Michael R., Moore, T.E., Ogilvie, K.W., et al. Observations of neutral atoms from the solar wind. J. Geophys. Res., 106, 24,893-24,906, 2001.

[4] Collier, Michael R., Moore, T.E., Ogilvie, K., et al. Dust in the wind: The dust geometric cross section at 1 AU based on neutral solar wind observations. Solar Wind Ten, Proceedings of the Tenth International Solar Wind Conference. M. Velli, R. Bruno and F. Malara (eds.), AIP Conf. Proceedings Volume 679, American Institute of Physics, Melville, New York, pp. 790-793, 2003.

[5] Collier, Michael R., Moore, T.E., Simpson, D., et al. An unexplained 10-40° shift in the location of some diverse neutral atom data at 1 AU. Adv. Space Res., 34, 166-171, 2004.

[6] Dalin, P., Zastenker, G., Paularena, K., et al. The main features of solar wind plasma correlations of importance to space weather strategy. Journal of Atmospheric and Solar-Terrestrial Physics, 64, 737-742, 2002.

[7] Geiss, J., Witte, M., Properties of the interstellar gas inside the heliosphere. Space Sci. Rev., 78, 229-238, 1996.

[8] Moore, T.E., Chornay, D.J., Collier, M.R., et al. The Low Energy Neutral Atom Imager for IMAGE. Space Science Reviews, 91, 155-195, 2000.

[9] Moore, T.E., Collier, M.R., Burch, J.L., et al. Low Energy Neutral Atoms in the Magnetosphere. Geophys. Res. Lett. 28 , 1143-1146, 2001.

[10] Moore, T.E., Collier, M.R., Fok, M.-C., et al. Heliosphere-Geosphere Interactions Using Low Energy Neutral Atom Imaging. Space Sci. Rev., 109, 351-371, 2003.

[11] Paularena, K.I., Zastenker, G.N., Lazarus, A.J., et al. Solar wind plasma correlations between IMP 8, INTERBALL-1, and WIND. J. Geophys. Res., 103, A7, 14601-14617, 1998.

[12] Ratkiewicz, R., Barnes, A., Molvik, G.A., et al. Effect of varying strength and orientation of local interstellar magnetic field on configuration of exterior heliosphere: 3D MHD simulations. Astron. Astrophys., 335, 363-369, 1998.

[13] Richardson, J.D., Paularena, K.I., Plasma and Magnetic Field Correlations in the Solar Wind. J. Geophys. Res., 106, A1, 239-251, 2001.

[14] Schwadron, N.A., Geiss, J., Fisk, L.A., et al. Inner source distributions: Theoretical interpretation, implications, and evidence for inner source protons. J. Geophys. Res., 105, A4, 7465-7472, 2000.

[15] Zastenker, G.N., Dalin, P., Paularena, K.I., et al. Solar wind correlation features obtained from a multi-spacecraft study. Adv. Space Res., 26, 1, 71-76, 2000.